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Precision mechanisms for optical alignments at cryogenic temperatures

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ABSTRACT

The Lockheed Sensor Test Facility, located in Sunnyvale, California, is a state-of-the-art LWIR sensor calibration resource designed to calibrate strategic seekers against a simulated exoatmospheric optical background. Increasingly accurate and sophisticated seeker technology has created a demand for improved performance in test equipment, particularly in the area of cryogenic optical systems. Diffraction-limited optics and sub-arcsecond pointing have become the norm rather than the exception in these systems.

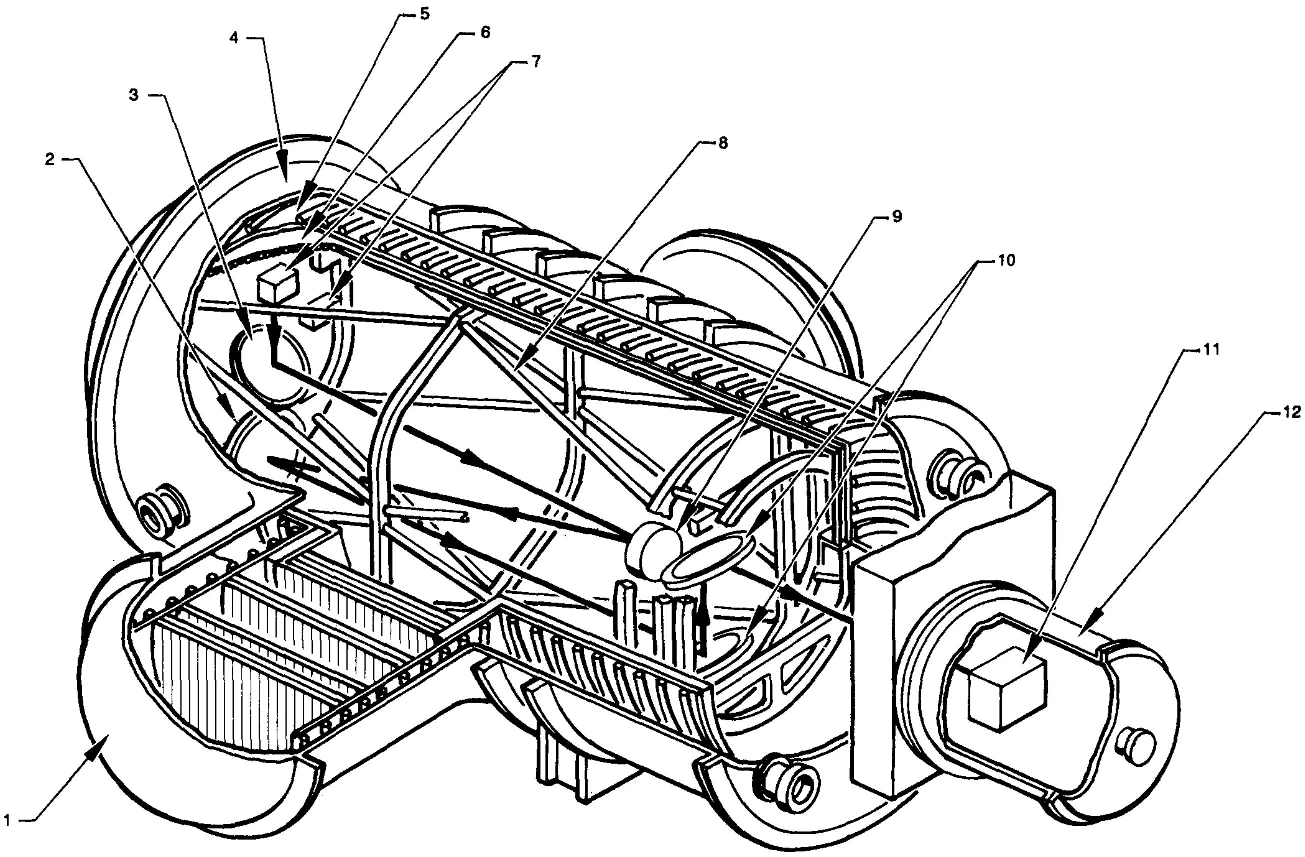
This paper chronicles the two-year development of several precision mechanisms for use in cryogenic environments to 20 K at pressures below 1 microtorr. The Lockheed mechanism development is highlighted by the successful adaptation of traditional mechanism design principles to the cryogenic environment through the judicious selection of materials, lubricants and electromechanical devices, and the appropriate use of both open- and closed-loop controls.

All of the mechanisms developed are associated with the 500-inch effective focal length, eccentric pupil Ritchey-Chretien collimator which forms the basis of the Lockheed seeker calibration approach. Although fundamentally athermal in design, this collimator has traditionally exhibited unacceptable warm-to-cold alignment variations. This phenomenon has been precluded through the use of a precision, six-degree-of-freedom refocusing mechanism which allows the *in situ* positioning of the collimator's secondary mirror. Together with two precision scan mirrors and their associated positioning mechanisms, the optical performance of the system at operating temperatures and pressures is assured. A source select mirror and its associated drive mechanism has been completely redesigned to provide the accurate positioning of several LWIR radiometric sources at the collimator prime focus.

1. INTRODUCTION

The Lockheed Sensor Test Facility (STF) is a helium cooled, low background infrared (LBIR) sensor calibration resource designed for the radiometric and metric calibration and characterization of infrared seekers. The STF main chamber, shown schematically in Fig. 1, contains a helium-cooled optical support assembly (OSA) on which are mounted a variety of optical components including the 500 inch EFL Ritchey-Chretien collimator, radiometric standards (blackbody sources), scan mirrors and associated light baffles. The OSA is shown in Fig. 2.

Associated with the STF optical system are several precision mechanisms which must operate with high reliability at temperatures between room ambient and 20 K, and at pressures from atmospheric to hard vacuum. The following paragraphs describe three of these mechanisms and the unique requirements that led to their development. Details relating to the selection of materials for cryogenic applications are included in an appendix. Of the three mechanisms, the collimator secondary refocus unit has been fabricated and tested extensively at temperatures to below 20 K. The source select mirror drive mechanism has been fabricated and tested at room temperature. Cryogenic testing will be conducted when the STF main chamber becomes available. The scan mirror drive mechanisms have been designed and are currently ready for fabrication. Installation and testing will be conducted early next year.



1 PUMPING APPENDAGE
2. PRIMARY MIRROR
3 SOURCE SELECTOR MIRROR
4. VACUUM CHAMBER
5 LIQUID NITROGEN CRYOSHIELD
6 20 K HELIUM CYROSHROUD
7. SOURCE ASSEMBLY
8. OPTICAL SUPPORT ASSEMBLY
9 SECONDARY MIRROR
10 SCAN MIRROR ASSEMBLY
11. TEST SENSOR
12 ANTECHAMBER

Fig. 1. STF thermal-vacuum chamber illustration

2. COLLIMATOR SECONDARY MIRROR REFOCUS UNIT

The STF collimator secondary mirror refocus unit, or refocusing mechanism, was conceived and developed in response to a chronic optical alignment problem. Although fundamentally athermal in design, the Ritchey-Chretien collimator had historically exhibited an unacceptable defocus when cooled from ambient to cryogenic temperatures. Extensive testing showed this defocus phenomenon to be hysteretic as well as temperature dependent. The hysteresis was eventually eliminated by preloading all bolted joints in the system, but the temperature dependence remained.

A careful review of the techniques used in the fabrication of the 24 inch primary mirror revealed that the electroless nickel coating deposited over the aluminum mirror substrate was not uniformly thick, nor was the coating the same thickness on the back surface as the reflecting surface. This coating asymmetry is the assumed cause of collimator defocus at cryogenic temperatures. The defocus is repeatable for a given operating temperature, and has been accommodated by introducing an appropriate amount of focus error into the collimator during room temperature alignment. The need to operate the collimator at several different temperatures without having to return to room temperature between each operation led to the development of the refocusing mechanism shown in Fig. 3.

Referring again to Fig. 2, the refocusing mechanism supports the collimator secondary mirror approximately 100 inches in front of the primary mirror and provides six separate adjustments of the secondary mirror position. A unique characteristic of the Ritchey-Chretien optical prescription is that a small axial movement of the secondary mirror results in a relatively large focus shift. Specifically, the ratio of focus shift to secondary mirror position at or near proper alignment is 15:1. In addition to translation along the collimator optical axis (focus), the adjustments allow the *in situ* alignment of the collimator, and include: translation perpendicular to the collimator optical axis (vertical and horizontal decenter), pitch and yaw of the mirror segment, and rotation about the mirror segment surface normal. The implementation of these adjustments is shown on an isometric drawing of the mechanism in Fig. 4. Note that this implementation utilizes flexural pivots for all adjustments except focus, causing the decenter adjustments to couple with the pitch and yaw adjustments.

Each of the six adjustments is accomplished by the precision actuator shown in Fig. 5. Each actuator converts the rotation of a conventional stepper motor into linear movement through the use of a precision gear reducer coupled to a precision lead screw. The movement of the screw is opposed by springs to provide bi-directional operation without backlash. A conventional AC LVDT coupled directly to the lead screw senses the position of the actuator. The actuator housings were fabricated from titanium to ensure that the steel gears remain appropriately meshed at cryogenic temperatures, and to minimize heat conduction from the motors to the OSA. All internal components were carefully cleaned and coated with molybdenum disulfide prior to assembly. Each assembly was "run in" at room temperature for 12 hours at 1500 RPM to ensure smooth operation at all temperatures. A summary of the functional features of the refocusing mechanism is included in Table 1.

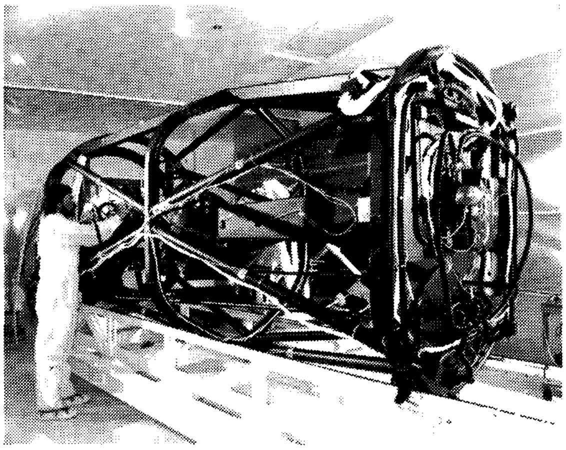


Fig. 2. STF optical structure

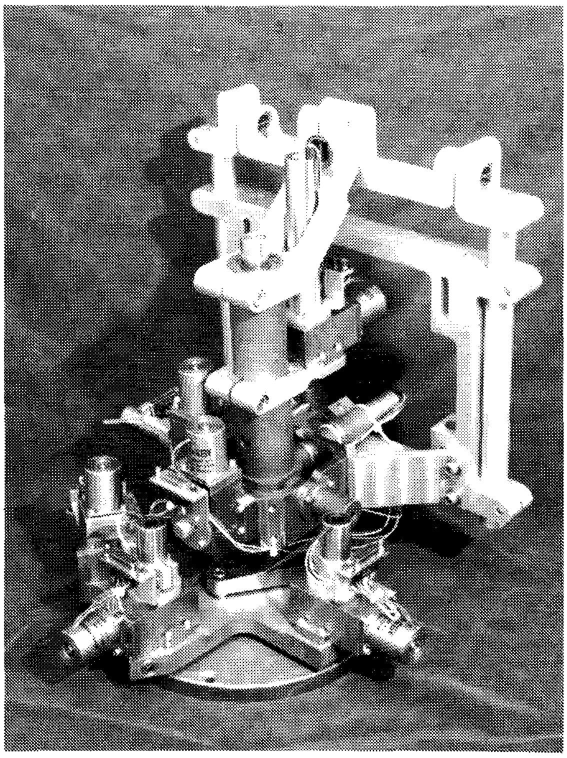


Fig. 3. STF collimator secondary mirror refocus unit

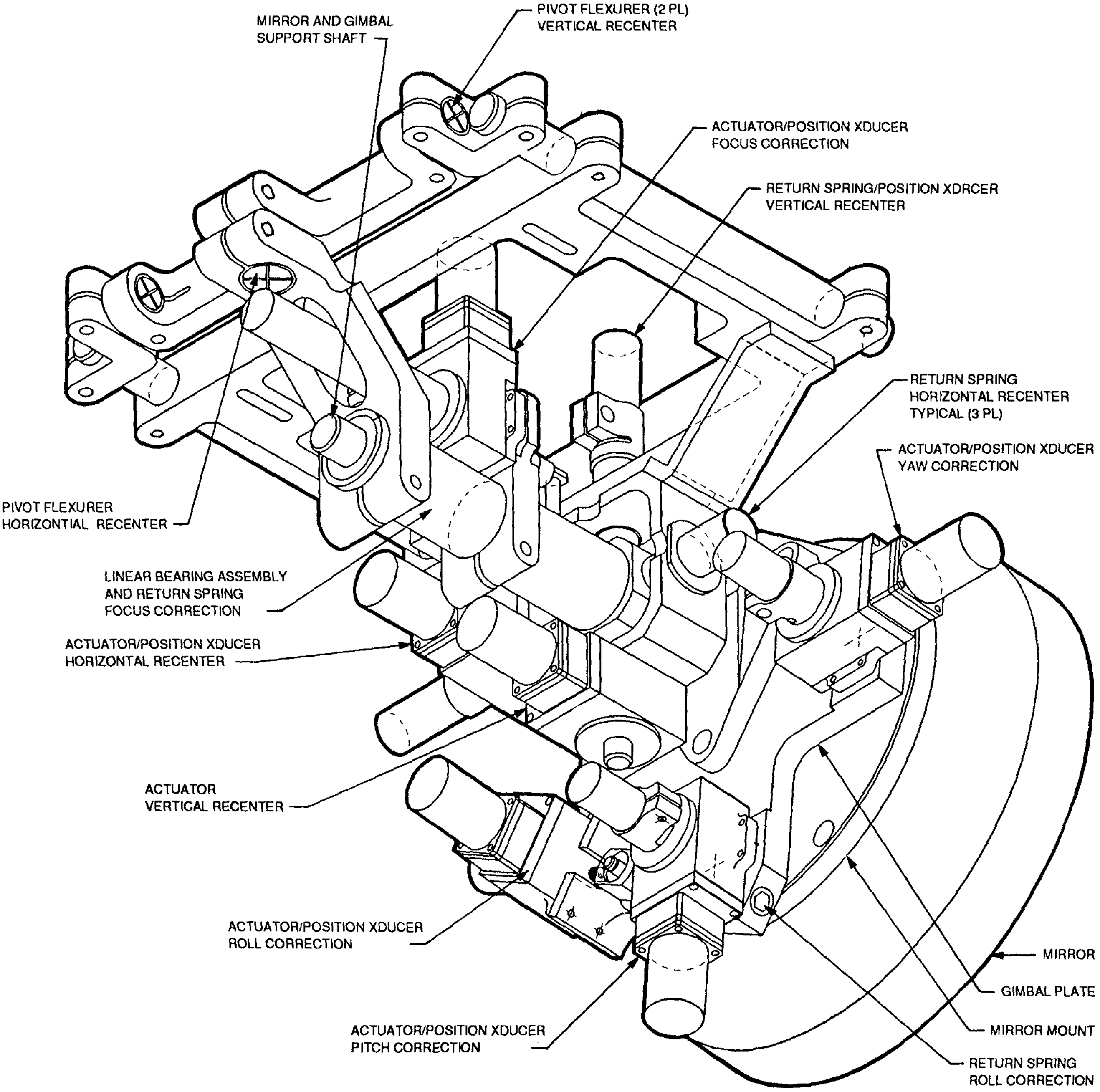
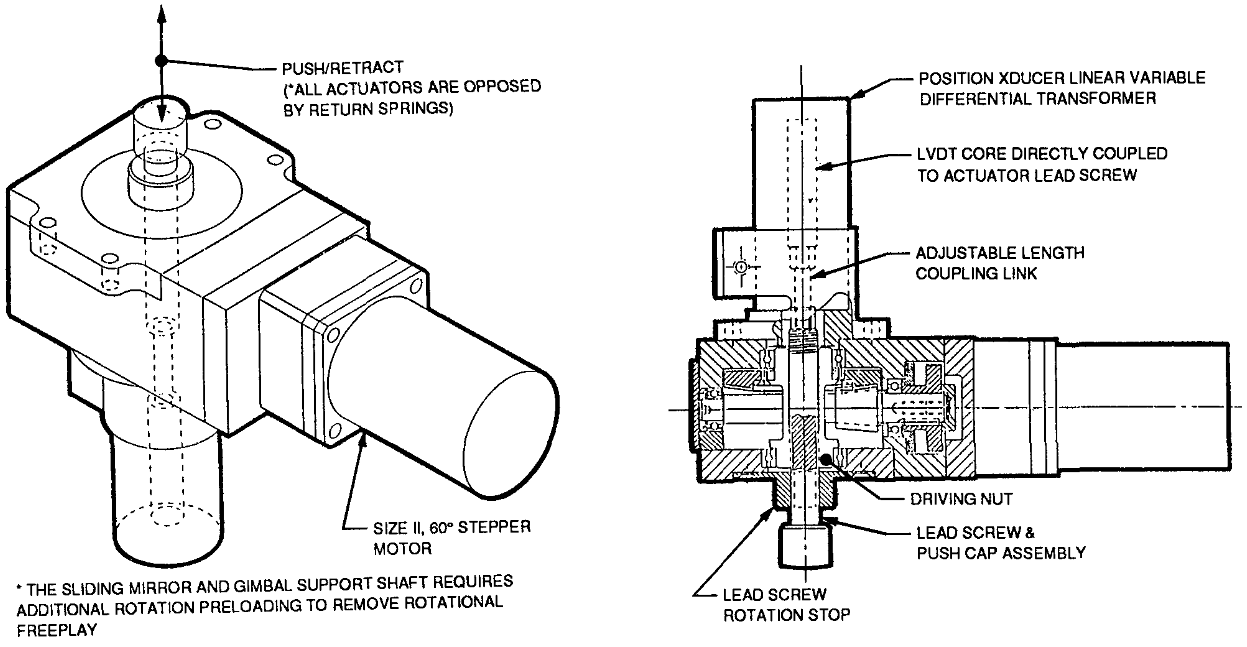


Fig. 4. STF collimator secondary mirror refocus unit illustration

Fig. 6 shows an illustration of the simple computer-controlled operating system used for the refocusing mechanism control. Virtually all components are standard, off-the-shelf PC/XT compatible cards. Several short BASIC programs provide remote manual control of each actuator, and display the output of each LVDT position. A block diagram of the control system is shown in Fig. 7.



a. actuator illustration

b. actuator cross section

Fig. 5. STF refocusing mechanism actuator details

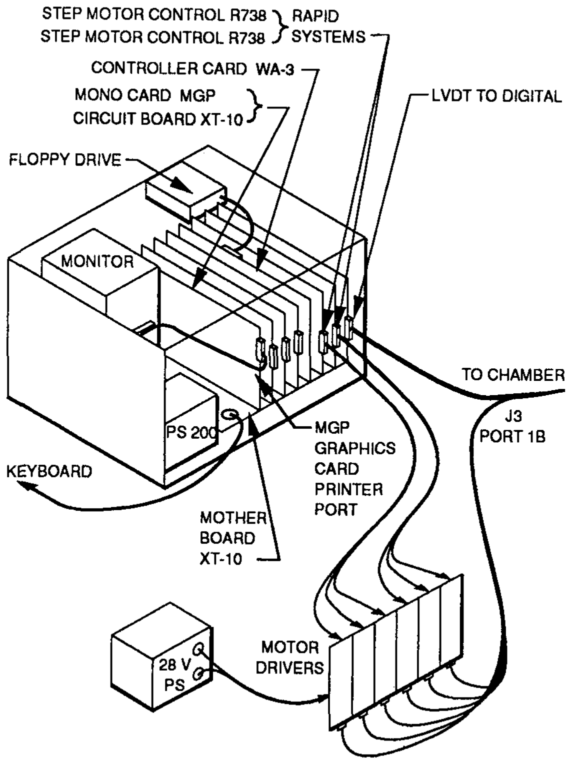


Fig. 6. Refocusing mechanism operating system

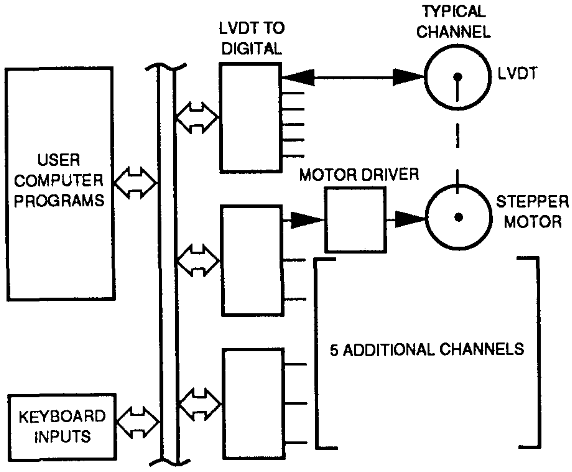


Fig. 7. Refocusing mechanism control system block diagram

Table 1. Refocusing mechanism functional features

1. Adjustment capability (referred to center point of mirror)

correction	range	per motor step
focus	±0.80 in	$14.0X10^{-6}$ in
vertical	±0.49 in	$21.6X10^{-6}$ in
horizontal	±0.49 in	$21.6X10^{-6}$ in
pitch	±5.0 deg	$4.1X10^{-6}$ rad
yaw	±5.0 deg	$4.1X10^{-6}$ rad
roll	±2.8 deg	$4.1X10^{-6}$ rad

2. All adjustments are spring loaded to eliminate lost motion
3. Housing, gear and bearing materials have been selected to provide slightly increased running clearances as temperatures are reduced
4. Decentering adjustment will be accompanied by changes in pitch and yaw angles
5. Pitch and yaw adjustments will be accompanied by lateral center shifting

3. SOURCE SELECT MIRROR DRIVE MECHANISM

Referring again to Fig. 1 and 2, several radiometric sources and alignment aids are arrayed at the collimator prime focus, and are selected for use individually by rotating a flat mirror oriented at 46.5° to the collimator chief ray. The axis of rotation of the mirror is colinear with the chief ray and 3° below the collimator optical axis, allowing the sources and alignment aids to be located in a plane perpendicular to the collimator optical axis. The rotating flat, known as the source select mirror, folds the system approximately 11 inches ahead of the collimator prime focus, thus providing ample room for a variety of devices to be located within the 200 degrees of mirror rotation capability.

The desire to use more than one source during sensor calibration, or to verify collimator alignment between sensors without disturbing the cryogenic environment, led to the requirement that the source select mirror be positioned with a accuracy not previously available. Specifically, any given source position had to be repeatable to within ±10 μrad with respect to the sensor being calibrated. To satisfy this requirement the source select mirror drive mechanism shown in Fig. 8 was developed.

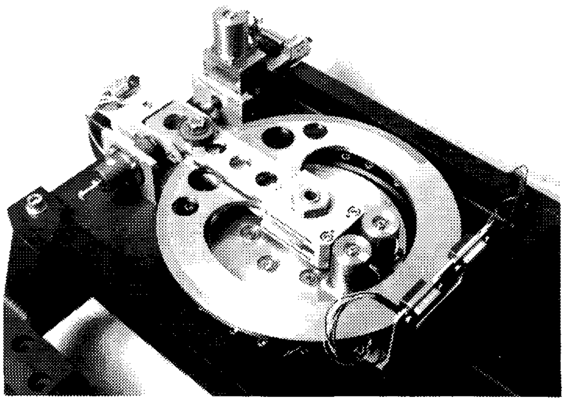


Fig. 8. Source select mirror drive mechanism

The source select mirror drive mechanism features a rapid, coarse positioning of the mirror anywhere within a 200° operating range. Coarse positioning is accomplished by two stepper motors and two reducing gear sets driving a common bull gear on the mirror support rotor. This rotor is rigidly supported by a pair of preloaded angular contact bearings which allow differential thermal expansion of the rotating elements while maintaining adequate stiffness to support the source select mirror. The two motors used are the same as those used in the refocusing mechanism discussed previously, and were chosen over a single, larger motor for packaging efficiency and proven cryogenic design. Two motors provide necessary torque margin with the relatively small reduction ratio necessary to allow back driving. A dual (1 speed X 16 speed) resolver is used to establish the nominal position of the mirror which can be set within 0.07° by a single 60° step of either motor. Viewed from the output of the 500 inch EFL collimator, this coarse positioning capability places the source within 27 µrad of the desired position.

Operation of the coarse positioning feature requires the release of a braking mechanism (seen clearly near the top, left side of Fig. 8) which utilizes a spring loaded, normally closed caliper to fix the initial position of the mechanism. The caliper is released by a solenoid which is heat strapped to the structure to allow continuous operation at 0.5 ampere without heating the source select mirror. The brake mechanism also acts as a lever arm for the fine positioning of the mirror. The lever is moved by an actuator similar to those used in the refocusing mechanism (Fig. 5), and provides a fine resolution of 12 µrad per 30° motor step (0.26 µrad relative to the collimator output). As in the refocusing mechanism, the actuator position is sensed by an AC LVDT attached directly to the actuator screw.

The motor control and position feedback operating system is shown in the block diagram of Fig. 9. As with the refocusing mechanism, all control system components are standard PC/XT cards, and BASIC programs provide a user-friendly interface to the system. The source select mirror drive mechanism is shown in detail, with components labeled, in Fig. 10 and 11. The main features of the mechanism are summarized in Table 2.

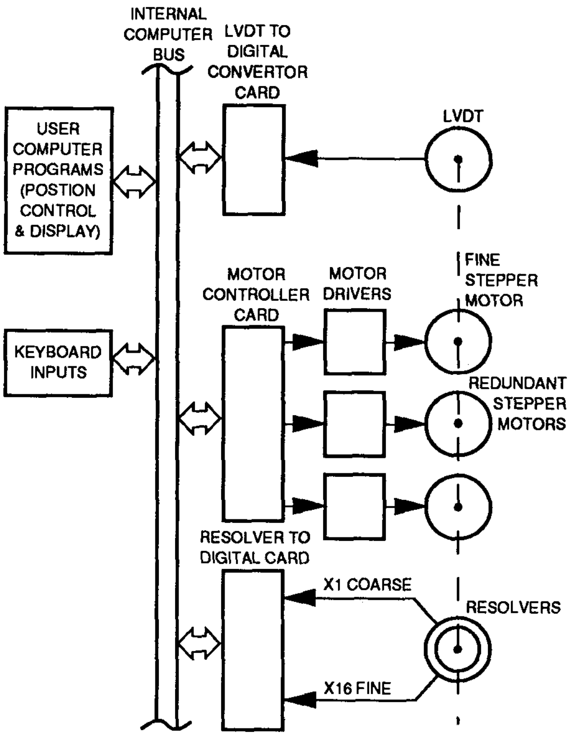


Fig. 9. Source select mechanism control system block diagram

4. SCAN MIRROR DRIVE MECHANISM

When the OSA was originally built in 1980-81, two large, lightweighted aluminum scan mirrors were provided to allow movement of the radiometric sources in azimuth and elevation relative to the sensor under test. Weighing over 150 pounds each, the scan mirrors were attached by their edges directly to shafts and pivoted on (nearly) frictionless, rotating knife edges. The control system used to move the mirrors was designed to take advantage of the virtually pure inertial mass, and provided impulsive torques to initiate constant angular velocity scans across the sensor field of view.

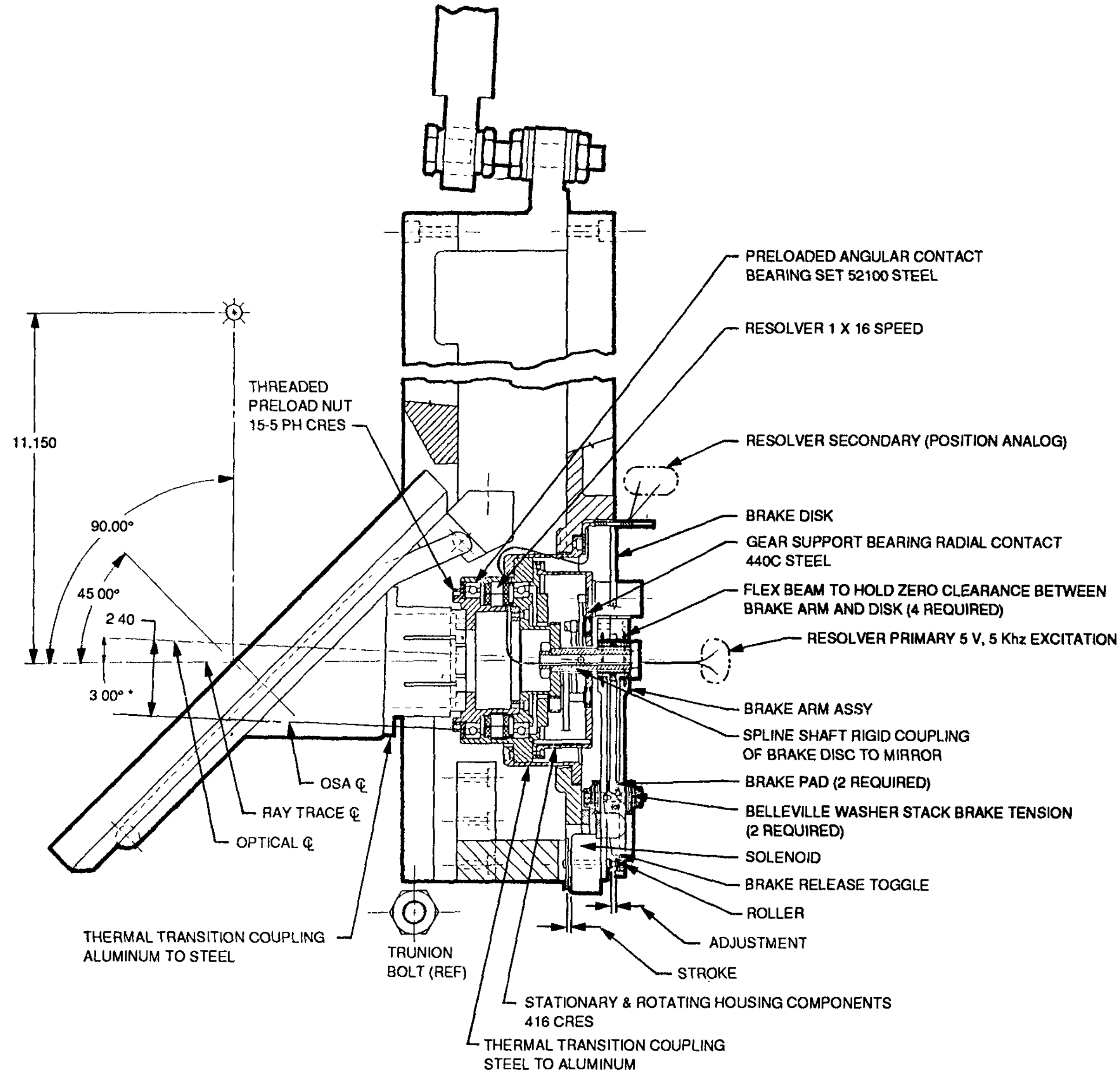


Fig. 10. Refocusing mechanism cross section illustration

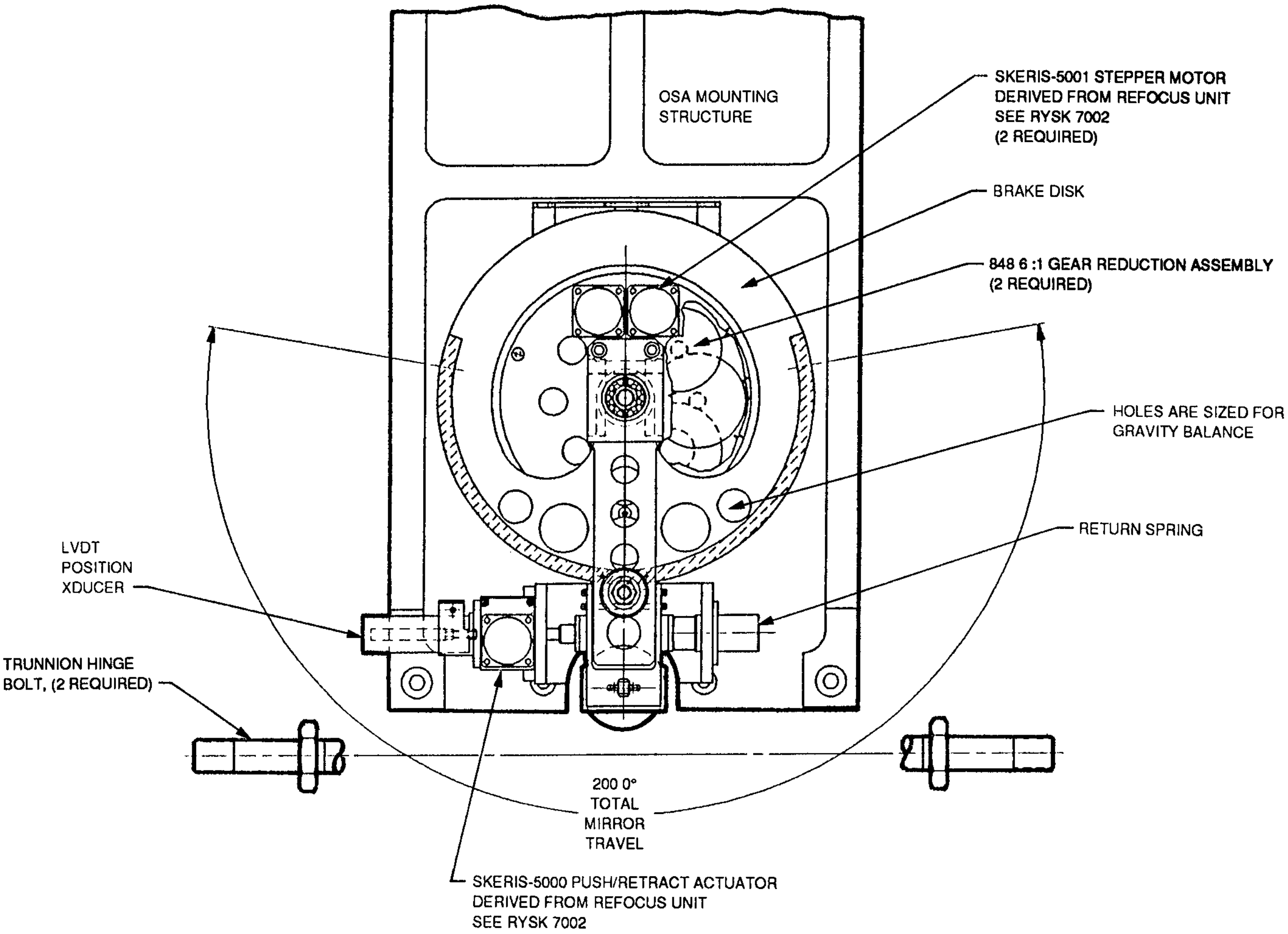


Fig. 11. Refocusing mechanism elevation view (truncated)

Table 2. Source select mechanism functional features

1. Adjustment capability

resolution	mechanical	readout	
coarse	0.07 deg	23.9 μrad	(resolver)
fine	0.0007 deg	1.9 μrad	(LVDT)

2. Ratio selected nearest to high limit while still permitting backdriving
3. Motor and gear set doubled for torque margin
4. Solenoid heat strapped for 0.5 ampere continuous duty

As a result of improper mounting, and possibly inadequate thermal cycling during manufacture, both scan mirrors developed unacceptable distortions over a period of several years and numerous temperature cycles between room ambient and 20 K. The mirrors were replaced in 1988 with smaller, properly mounted beryllium mirrors which have maintained figure through several dozen temperature cycles. Attendant with the mirror replacement, the control system was modified to accommodate a new generation of sensors with more complex focal plane geometries, more detectors on the focal plane, and step-and-stare calibration requirements. In 1989 the decision was made to replace both scan mirror drives with a more robust, high-precision positioning system designed to accommodate sensors with increased angular resolution and as many as several hundred thousand detectors per focal plane. The new mechanism design is illustrated in Fig. 12 (azimuth configuration shown).

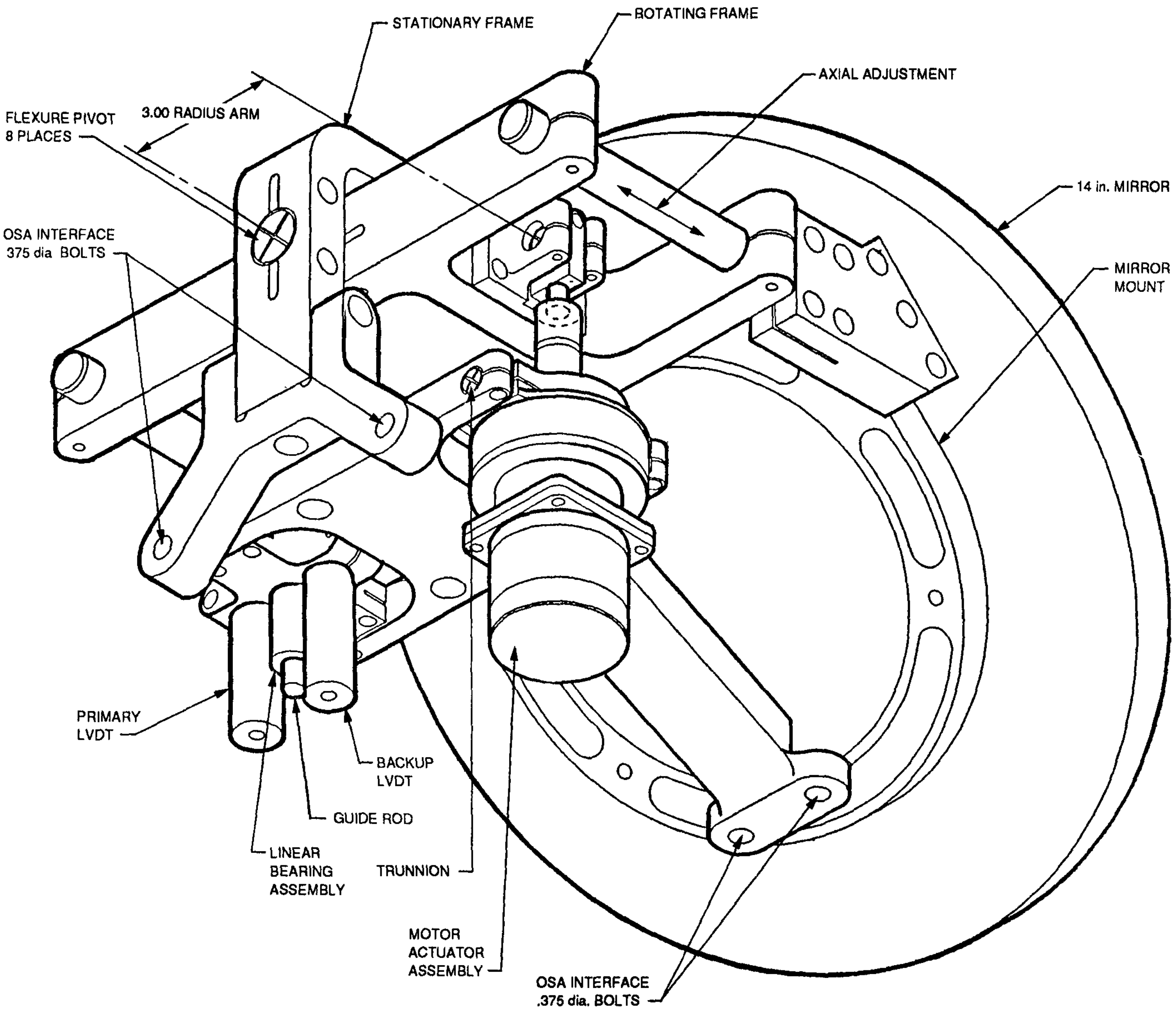


Fig. 12. Scan mirror drive mechanism (azimuth configuration)

Taking advantage of the successful adaptation of conventional stepper motor technology to cryogenic environments, the scan mirror drives each employ the trunion mounted actuator shown in Fig. 13. A 200 step/revolution stepper motor drives a proprietary 69:1 epicyclic speed reducer (zero backlash) through a small 3:1 planetary reducer to rotate a precision recirculating ball nut around a matched .125 inch pitch ball screw. The resultant movement of the ball screw is 3 μin per motor step, with less than 0.3 μin reversal error associated with the 3:1 planetary reducer. When attached to the scan mirror support structure 3.0 inches from the axis of rotation of the mirror, the actuator provides 1 μrad of mirror rotation for each motor step at speeds up to 10 mrad/sec (10,000 steps/sec). Conventional microstepping techniques allow even finer positioning resolution at the expense of speed.

Mirror position is sensed by a pair of AC LVDTs also located 3.0 inches from the axis of rotation of the mirror. Two units were chosen for redundancy, although series wiring allows a doubling of resolution to 1 μrad using standard 16-bit LVDT-to-digital converter technology. The cosine error associated with the linear to angular conversion, as well as tolerance variations in the lead screw, are removed by calibration. The control system for the scan mirror drives is essentially the same as shown in Fig. 7 and Fig. 9, although closed loop position and velocity control is planned to accommodate automated sensor testing.

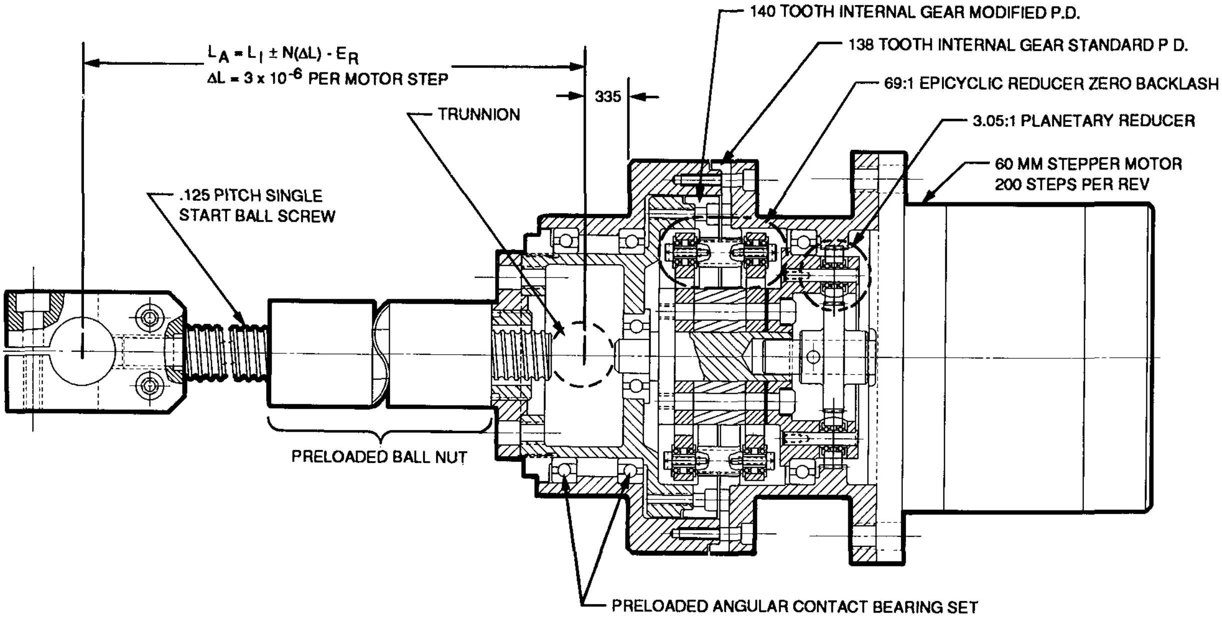


Fig. 13. Scan mirror drive mechanism actuator

APPENDIX A. MATERIAL SELECTION

Table A1. Refocusing mechanism materials

Assembly	Part	Material
Actuator	housing	6AL-4V Ti
	spiral gear set	brass gear & 303 SS pinion
	bearings	440C cres
	input reduction gear	brass
Motor reducer	housing	416 cres
	bearings	440C cres
	gears	416 cres & 17-4 PH SS
Motor	housing	416 cres
	bearings	440C cres
	pinion shaft	303 SS
Focus slide assy	housing	416 cres
	bearings	440C cres
	shaft	440C cres
Pitch/yaw gimbal plate		6AL-4V Ti
OSA transition structure	vert/horiz recenter frame	6AL-4V Ti
	slide assy strut	6061-T6 Al
	installation adjust frame	6061-T6 Al

Table A2. Source select mechanism materials

Assembly	Part	Material
Main housing assy	housing	416 cres
	rotor	416 cres
	spacers	416 cres
	bearings	52100 steel*
	preload nut	15-5 PH SS
Gear housing	housing	416 cres
	bearing plate	416 cres
	bearings	440C cres
	gear clusters	416 cres & 15-5 PH SS
Brake assy	spline shaft	15-5 PH SS
	disc	naval brass
	caliper arm	17-4 PH SS
	friction pads	6061-T6 Al
	arm pivot bushing	rulon (LD)
Motor		same as refocus unit
Mirror transition coupling		6061-T6 Al
Bulkhead transition coupling		6061-T6 Al

*To be replaced by 440C when available (special order). 52100 may lose preload at 20 K.

Table A3. Scan mirror mechanism materials

Assembly	Part	Material
Actuator	housing	416 cres
	rotor	416 cres
	rotor bearings	52100 steel*
	gear support bearings	440C cres
	gears	416 cres & 15-5 PH SS
	ball screw	17-4 PH SS
	ball nut	17-4 PH SS
	balls	440C cres
Motor		not defined
Stationary frame (drive)		6061-T6 Al
Rotating frame (drive)		6061-T6 Al
Flex pivots		440C cres
Actuator/LVDT support structure		6061-T6 Al
Stationary frame (follow)		6061-T6 Al
Rotating frame (follow)		6061-T6 Al

Table A4. Lubricants (all mechanisms)

Lubricant	Application	Remarks
Unbonded MoS_2	ball bearings & gears with near zero backlash	-applied by impinging -should be burnished -surfaces hard & ground to .000006" -gear surfaces may become exposed
Bonded MoS_2	gears w/ backlash & lead screw	-spray on, heat cure -coating may be fairly thick (.002") -friction stabilized by run-in
Teflon solid	bushings from reinforced bar stock	-lower friction than MoS_2, lower allowed loads
Teflon powder	used with MoS_2 to reduce friction	-wear life not yet established

General remarks:

The friction coefficient of a dry lubricant system will increase as the unit loads (P/A) increase. The torque margin is reduced as temperature is reduced to 20 K. To ensure that unit loads remain low and theoretical torque margin high, overdesigning by a factor of 3 to 5 is recommended.